

Solid-State Reactions and Dielectric Properties in the System Magnesia-Lime-Tin Oxide-Titania¹

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A study has been made of solid-state reactions in the quaternary system $\text{MgO-CaO-SnO}_2\text{-TiO}_2$ and in its subordinate binary and ternary systems. Compatibility relations have been determined for each. Extensive solid-solution formation has been noted in the $\text{SnO}_2\text{-TiO}_2$, $\text{MgO-SnO}_2\text{-TiO}_2$, $\text{CaO-SnO}_2\text{-TiO}_2$, and $\text{MgO-CaO-SnO}_2\text{-TiO}_2$ systems. Little or no solid solution was observed in the other systems involved. One ternary compound, having the probable formula $2\text{MgO-SnO}_2\text{-TiO}_2$, has been observed. No quaternary compounds were detected.

A survey has been conducted of the effect of composition and temperature variations on the dielectric properties of specimens in some of these systems. Data are given for the values of K and Q at 50 kilocycles per second, and at 1 and 20 megacycles per second. The changes in these values with changes in temperature have been studied at 1 megacycle per second.

Indexed X-ray powder patterns are listed for the compounds CaO-TiO_2 , CaO-SnO_2 , and $2\text{MgO-SnO}_2\text{-TiO}_2$.¹ An unindexed pattern is given for the compound 2CaO-SnO_2 .

1. Introduction¹

A partial survey of the $\text{MgO-CaO-SnO}_2\text{-TiO}_2$ system has been conducted as a part of a program of fundamental research on ceramic dielectrics. Limited portions of a few of the subsystems involved have been studied by previous investigators. The MgO-TiO_2 system has been reported on by Rieke and Ungewiss [1]² and by Shelton et al. [2]. The properties of dielectrics in the CaO-TiO_2 system have been reported by Bunting et al. [3]. Dielectrics in the $\text{SnO}_2\text{-TiO}_2$ system were studied by Schusterius [4] and by Verwey and Stevels [5]. Wainer [6] received a number of patents for dielectric bodies composed of alkaline-earth titanates and alkaline-earth stannates. Coffeen [7] has discussed the ceramic and dielectric properties of some individual stannates.

In the present work, the emphasis has been on the study of solid-state reactions occurring among the oxide components, and the effects of composition and temperature on dielectric properties, rather than on the development of ceramic dielectrics having specific properties or meeting any given set of specifications.

2. Materials and Methods

2.1. Materials

The following materials were used as sources of the component oxides in this study:

MgO.—Reagent-grade magnesium carbonate of purity represented as 99.5 percent was the usual source material. However, in the fabrication of a few of the dielectric test specimens, a sample of periclase of 96.4-percent purity was used.

CaO.—Reagent-grade calcium carbonate of purity represented as 99.5 percent.

TiO₂.—Spectrographic-grade titania of nominal purity over 99.9 percent was used in all specimens for the solid-state studies. In the preparation of some of the dielectric test specimens, a less highly purified grade of titania, designated TMO, was used. This grade of titania has a purity of about 98.7 percent. A commercial-grade calcium titanate was used in the preparation of a few dielectric test samples. This material has a nominal purity of 96.5 percent, the major impurities being MgO , SiO_2 , and Al_2O_3 .

SnO₂.—Precipitated tin oxide of purity over 98.5 percent. Hydrated, precipitated magnesium stannate and calcium stannate were used as source materials in some cases. The calcium stannate was used wherever possible in dielectric test specimens. These materials both have a nominal purity over 99.5 percent.

2.2. Sample Preparation

Compositions to be prepared were designated on a mole-ratio basis, and calculations of the weight compositions were made to ± 0.01 percent. No corrections were made for the percentage purity of the raw materials, although it is realized that dielectric properties may be affected by the presence of different kinds and amounts of impurities.

The raw materials in sufficient amounts to yield a 10-g sample were weighed to the nearest milligram and well mixed in the dry state. The samples were then mixed with about 5 percent of a 5-percent starch-solution binder, and 1-in.-diameter disks were formed at a pressure of 5,000 lb/in². The pressed disks were calcined for 4 hours at 1,000° to 1,200° C on platinum foil in an oxidizing atmosphere. The calcined disks were pulverized, using a mullite mortar and pestle, and the samples were ready to be used either for the solid-state studies or for pressing into dielectric specimens. No chemical analyses were made after the firing.

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² Figures in brackets indicate the literature references at the end of this paper.

2.3. Study of Solid-State Reactions

In the study of solid-state reactions, a conventional type platinum-wound quench furnace was used. The temperature in the furnace was measured with a Pt-Pt-10-percent-Rh thermocouple and was controlled by a modified Roberts-type controller. The quenching technique was used in order that high-temperature solid solutions could be observed. For quench tests, a small amount of the prepared sample was placed in a platinum envelope, which was then suspended in the furnace. The test temperature ranged from 1,400° to 1,550° C and was maintained constant for a given length of time. After this reaction time, the sample was quenched, usually in air. In some cases, water or carbon tetrachloride was used as the quenching medium.

Alternatively, samples were heated to temperatures as high as 1,750° C and were cooled relatively slowly. The quenched or slowly cooled specimens were then analyzed by X-ray diffraction means and by petrographic methods.

These procedures are, in general, similar to those discussed by Foster [8].

2.4. Preparation of Dielectric Test Specimens

The prepared samples were moistened with about 5 percent of starch-solution binder, and disks about $\frac{1}{8}$ in. thick and $\frac{1}{2}$ to $1\frac{1}{2}$ in. in diameter were formed at a pressure of 10,000 to 15,000 lb/in.² The pressed disks were fired for $\frac{1}{2}$ to 1 hour on platinum foil in an oxidizing atmosphere. Maturing temperatures varied from 1,400° to 1,750° C, depending upon the composition and the raw materials used. For maturing temperatures up to 1,550° C, a platinum-wound resistance furnace was used. Temperatures were measured with a Pt-Pt-10-percent-Rh thermocouple and were controlled by an automatic commercial controller-recorder. For maturing temperatures higher than 1,550° C, an oxide-resistor furnace [9] was used. This furnace was manually controlled, and temperatures were measured with a calibrated optical pyrometer.

The fired specimens were then used to determine their absorption value, which is a convenient measure of the degree of maturity. The absorption was determined by placing the weighed disk in chemically pure carbon tetrachloride. The liquid was boiled for 5 hours and allowed to cool. The specimen was removed from the liquid, quickly surface dried, and weighed in a stoppered bottle. From the gain in weight, the equivalent water absorption was calculated. A specimen was considered to be properly matured when its equivalent water absorption was 0.1 percent or less of the dry weight.

Some compositions could not be fired to an imperious condition, and, in these cases, dielectric tests were performed on specimens having an absorption value greater than 0.1 percent.

2.5. Determination of Dielectric Properties

At frequencies between 50 kc/s and 20 Mc/s and at temperatures between 25° and 250° C, the dielec-

tric constant (K) and the Q -value (when greater than 10, the Q -value is very nearly equal to the reciprocal of the power factor) were determined by measurements on a Q -meter. The test specimens were coated on each side with a silver paste and fired to 750° C to form silver electrodes 3 to 5 mils thick. The specimen was then cooled overnight. Preliminary determinations were made at a temperature of $25^\circ \pm 0.5^\circ$ C, and at a controlled relative humidity of 40 percent or less.

For measurements at temperatures greater than 25° C, the specimens were placed on an electric hot-plate and were connected to the Q -meter by 10-in. leads. The temperature was controlled by means of an adjustable autotransformer and was measured by means of a thermocouple inserted into a silvered ceramic disk adjacent to the specimen. Correction factors for the capacitance and inductance of the lead wires were applied.

For measurements in the temperature range between -50° and 25° C, the specimens were placed in an insulated chamber cooled by dry ice. The temperature was controlled by a thermostat and was measured by means of a liquid-in-glass thermometer. The measurements were made at a frequency of 1 Mc/s and were obtained by using a type 820A twin-T impedance circuit combined with a model HRO-50T radio receiver. Corrections for the capacitance and inductance of the lead wires were applied.

For a given specimen, the reproducibility of measurements of dielectric constant is about ± 3 percent, depending upon the dimensions and capacitance of the sample. For different specimens of the same gross composition, additional variations of K -values result from factors such as differences in firing schedules, purity of raw materials, etc.

3. Results of Solid-State Reaction Studies

3.1. Binary Systems

a. MgO-TiO₂

Three binary compounds are known to exist in the MgO-TiO₂ system [10]. They are 2MgO·TiO₂, MgO·TiO₂, and MgO·2TiO₂. There is no solid-solution development in this system.

b. CaO-TiO₂

There are two binary compounds in this system [11]. They are CaO·TiO₂ and 3CaO·2TiO₂. The X-ray pattern for 3CaO·2TiO₂ has been given in a previous publication [11]. The indexed powder pattern for CaO·TiO₂ is listed in table 1. This compound is an orthorhombic perovskite with the following pseudocubic-type parameters, as suggested by Megaw [12].

$$\begin{aligned}a &\cong \sqrt{2} \times \text{basic pseudocell} = 5.381 \text{ \AA}, \\b &\cong 2 \times \text{basic pseudocell} = 7.645 \text{ \AA}, \\c &\cong \sqrt{2} \times \text{basic pseudocell} = 5.443 \text{ \AA}.\end{aligned}$$

TABLE 1. X-ray diffraction pattern for the compound CaO·TiO₂

hkl	1/d ² obs.	1/d ² calc.	R. I. ^a	hkl	1/d ² obs.	1/d ² calc.	R. I. ^a
101	0.068	0.068	30	333	.7681	.7686	7
111	.085	.085	7	162	.7840	.7855	2
002	.135	.135	51	044	.8134	.8138	18
121	.137	.137	100+	440	.8260	.8263	14
200	.138	.138	70	070	.8352	.8384	5
012	.152	.152	4	144	.8480	.8483	4
102	.169	.170	4	170	.8726	.8729	3
201	.172	.172	6	105	.8776	.8784	5
112	.186	.187	5	115	.8949	.8955	7
211	.189	.189	17	171	.9065	.9067	3
022	.203	.203	12	125	.9464	.9468	12
220	.206	.207	11	244	.9518	.9520	21
131	.222	.222	6	163	.9542	.9543	21
122	.238	.238	5	361	.9606	.9605	38
221	.240	.240	4	521	.9654	.9655	40
202	.273	.273	80	135	1.0321	1.0324	7
040	.274	.274	78	404	1.0925	1.0926	8
032	.289	.289	6	254	1.0955	1.0959	6
212	.290	.290	7	414	1.1092	1.1097	3
132	.323	.324	2	145	1.1520	1.1521	5
231	.325	.326	2	305	1.1540	1.1547	5
103	.338	.338	5	541	1.1705	1.1709	4
222	.341	.342	7	006	1.2146	1.2151	4
141	.342	.342	5	325	1.2229	1.2231	16
113	.355	.355	9	363j	1.2310	(1.2306)	29
311	.361	.362	4	016j		(1.2322)	
123	.407	.407	29	523	1.2357	1.2356	28
042	.409	.409	32	372	1.2840	1.2842	4
240	.412	.412	34	155	1.3059	1.3061	6
321	.413	.413	39	335	1.3084	1.3086	5
241	.445	.446	3	206	1.3530	1.3533	6
150	.462	.462	4	282j	1.3668	1.3681	16
133	.492	.492	8	036j			
004	.540	.540	6	216	1.3695	1.3691	22
242	.547	.547	29	090	1.3852	1.3859	4
400	.552	.553	7	226	1.4218	1.4217	5
104	.574	.575	3	345	1.4284	1.4284	5
401	.586	.586	4	191	1.4542	1.4542	4
152	.597	.597	7	046	1.4896	1.4889	9
332	.600	.600	6	165	1.4949	1.4943	4
143	.611	.612	6	561	1.5143	1.5131	13
313	.631	.632	5	640	1.5179	1.5171	12
204	.678	.678	7	355	1.5836	1.5824	2
323	.683	.683	12	326	1.5957	1.5944	3
161	.685	.684	15	246	1.6277	1.6270	9
402	.688	.688	10				
214	.6942	.6953	6				
252	.7002	.7009	5				
431	.7396	.7403	4				
153	.7660	.7661	7				

^a R. I. is the intensity of diffraction peaks relative to the strongest peak.

c. MgO·CaO

This system has been shown to contain a simple eutectic, with no compounds or solid solutions [13].

d. MgO·SnO₂

Only a brief study of this system was made, in order to verify previously published data [14].

The MgO·SnO₂ compositions studied are listed in table 2, together with the results obtained. X-ray and petrographic examination of these fired specimens indicated the existence of two binary compounds. They are 2MgO·SnO₂, which is thermally stable at temperatures as high as 1,550° C, and MgO·SnO₂, which decomposes into 2MgO·SnO₂ and SnO₂ between 800° and 1,000° C. The compound 2MgO·SnO₂ has a cubic spinel-type structure with $a=8.645$ Å and with an index of refraction equal to approximately 1.82. These results are in agreement with the work of Tanaka [14], but are somewhat at

variance with the results of Coffeen [7], who reported the compound MgO·SnO₂ to be thermally stable.

TABLE 2. Results of X-ray examination of specimens in the MgO·SnO₂ system

Mole ratio		Composition by weight		Heat treatment ^a		Phases identified
MgO	SnO ₂	MgO	SnO ₂	Time	Temperature	
		$\%$	$\%$	hr	°C	
4	1	51.70	48.30	6	1,550	MgO+2MgO·SnO ₂ .
2	1	34.86	65.14	19	1,550	2MgO·SnO ₂ .
1	1	21.11	78.89	66	800	MgO·SnO ₂ +trace SnO ₂ +trace 2MgO·SnO ₂ .
1	1	21.11	78.89	48	1,000	2MgO·SnO ₂ +SnO ₂ .
1	1	21.11	78.89	1	1,550	2MgO·SnO ₂ +SnO ₂ .
1	2	11.80	88.20	18	1,550	2MgO·SnO ₂ +SnO ₂ .

^a Each sample had been previously calcined for 4 hours at 1,100° C. The specimens were quenched in air from the temperature indicated.e. CaO·SnO₂

Two compounds were noted in this system. They are CaO·SnO₂, which has an orthorhombic perovskite structure, and 2CaO·SnO₂. These results agree with the findings of Tanaka [15]. An indexed powder pattern for the compound CaO·SnO₂ is given in table 3. The parameters of CaO·SnO₂ are:

$$a \cong \sqrt{2} \times \text{basic pseudocell} = 5.518 \text{ Å,}$$

$$b \cong 2 \times \text{basic pseudocell} = 7.884 \text{ Å,}$$

$$c \cong \sqrt{2} \times \text{basic pseudocell} = 5.664 \text{ Å.}$$

TABLE 3. X-ray diffraction pattern for the compound CaO·SnO₂

hkl	1/d ² obs.	1/d ² calc.	R. I. ^a	hkl	1/d ² obs.	1/d ² calc.	R. I. ^a
101	0.064	0.064	100+	153	-----	.7156	-----
111	.080	.080	7	044	.7561	.7562	6
002	.125	.125	63	440	.7829	.7830	5
121	.129	.128	100++	105	.8125	.8121	3
200	.131	.131	56				
201	.163	.163	4	343	.8343	.8336	6
211	.178	.179	7	262	-----	.8352	7
022	.189	.189	8	125	.8774	.8765	4
220	.196	.196	8	244	.8878	.8875	7
131	.209	.209	4	163	.8925	.8926	9
122	.222	.222	2	361	.9065	.9060	9
202	.256	.256	61	442	.9079	.9077	12
040	.257	.257	66	521	.9168	.9167	8
212	.272	.272	4	404	1.0248	1.0243	3
103	.313	.313	17	080	1.0296	1.0296	4
141/222	.321	.321	37	145	1.0701	1.0695	4
301	.327	.327	9	305	1.0752	1.0749	5
123	.378	.378	37	424	1.0894	1.0887	4
042	.382	.382	26	181	1.0941	1.0937	5
240	.389	.389	25	325	1.1397	1.1393	5
321	.391	.391	46	363	1.1553	1.1553	8
133	.459	.458	2	280	1.1612	1.1610	9
004	.499	.499	7	523	1.1666	1.1661	8
242	.514	.513	22	182	1.1870	1.1872	6
400	.526	.526	6	264	1.2105	1.2090	5
024	.563	.563	6	155	1.2159	1.2143	5
143	.571	.571	10	444	1.2825	1.2817	5
060	.579	.579	4	282	1.2864	1.2857	5
341	.584	.584	5	226	1.3184	1.3179	4
420	.590	.590	4	345	1.3325	1.3323	3
204	.630	.630	5	143	1.3436	1.3430	3
323	.641	.641	11	471	-----	1.3450	-----
161	.643	.643	16	165	1.3919	1.3913	4
402	.650	.650	6	561	1.4325	1.4315	8
224	.695	.694	6	316	-----	1.4339	-----
422	.7151	.7146	6	246	1.5119	1.5110	3
				642	1.5649	1.5646	5

^a R.I. is the intensity of diffraction peaks relative to the strongest peak.

The structure of the 2:1 compound has not been determined. Its X-ray diffraction pattern is listed in table 4.

The compositions studied in the CaO-SnO₂ system and the results obtained are given in table 5.

TABLE 4. X-ray diffraction pattern of the compound 2CaO·SnO₂

2θ	d	R. I. ^a	2θ	d	R. I. ^a
17.93	4.9	100	87.09	1.118	1
18.29	4.8	18	88.18	1.107	.5
24.00	3.70	5	89.96	1.089	.5
27.31	3.26	2	90.50	1.085	1
31.08	2.88	25	91.06	1.079	2
			92.36	1.068	5
31.74	2.82	77	92.80	1.064	7
32.87	2.72	80	92.91	1.063	6
33.04	2.71	32	93.19	1.060	6
36.29	2.47	7	93.48	1.058	6
37.04	2.42	10	93.90	1.054	5
40.33	2.23	12			
41.81	2.16	10	94.71	1.047	2
42.88	2.11	16	95.61	1.039	3
45.97	1.97	45	96.90	1.029	5
46.62	1.95	11	97.92	1.021	3
			98.94	1.013	1
48.34	1.88	7			
49.09	1.85	10	99.67	1.008	1
49.36	1.84	2	101.18	0.9969	4
49.54	1.84	3	101.56	.9942	3
50.83	1.79	2	102.13	.9902	3
			102.66	.9865	3
51.17	1.78	7			
55.67	1.65	10	105.09	.9703	0.5
56.28	1.63	14	107.56	.9543	.5
56.39	1.63	21	108.74	.9477	1
56.89	1.62	7	109.59	.9427	2
			109.90	.9409	4
57.06	1.61	15	110.06	.9399	4
57.47	1.60	22	110.57	.9371	8
58.94	1.57	3	111.82	.9301	2
59.56	1.55	7	112.32	.9273	3
61.59	1.50	2	112.64	.9256	4
63.08	1.47	9	113.66	.9202	5
64.20	1.45	3	115.87	.9089	2
64.77	1.44	3	116.99	.9034	3
65.54	1.42	3	118.14	.8979	1
65.68	1.42	6	119.43	.8919	3
66.05	1.41	14	120.09	.8890	3
66.23	1.41	13	120.92	.8853	2
67.88	1.38	8	122.75	.8775	0.5
68.74	1.36	4	125.00	.8684	.5
69.23	1.36	4	127.09	.8603	2
69.70	1.35	4	128.65	.8546	4
71.01	1.33	3	129.59	.8513	2
71.11	1.32	3	130.95	.8466	4
72.33	1.31	2	132.24	.8424	5
73.00	1.29	2	134.82	.8343	2
74.36	1.27	4	138.10	.8248	0.5
75.43	1.26	5	140.26	.8190	2
76.36	1.25	3	141.10	.8169	3
76.98	1.24	3	142.02	.8146	5
77.24	1.23	4	143.86	.8102	2
77.83	1.23	3	145.11	.8074	3
78.10	1.22	3	148.10	.8011	3
79.47	1.21	2	148.82	.7997	4
82.64	1.167	2	151.69	.7944	2
83.10	1.161	5	155.42	.7883	1
83.44	1.157	5	157.37	.7855	1
84.13	1.149	4	158.23	.7844	3
84.74	1.143	4	160.07	.7821	2
85.25	1.137	4	162.00	.7799	3
86.53	1.124	3	163.58	.7782	4

^a R. I. is the intensity of diffraction peaks relative to the strongest peak.

TABLE 5. Results of X-ray examination of specimens in the CaO-SnO₂ system

Mole ratio		Composition by weight		Heat treatment ^a		Phases identified
CaO	SnO ₂	CaO	SnO ₂	Time	Temperature	
		%	%	hr	° C	
4	1	59.82	40.18	18	1,400	CaO+2CaO·SnO ₂ .
5	2	48.19	51.80	40	1,300	CaO+2CaO·SnO ₂ .
2	1	42.67	57.33	3	1,550	2CaO·SnO ₂ +small amount CaO·SnO ₂ .
1	1	27.12	72.88	1	1,550	CaO·SnO ₂ .
1	2	15.69	84.31	17	1,400	CaO·SnO ₂ +SnO ₂ .
1	4	8.51	91.49	3	1,550	CaO·SnO ₂ +SnO ₂ .

^a Each sample had been previously calcined for 4 hours at 1,200° C. All samples were quenched in air from the temperature indicated.

f. SnO₂-TiO₂

This system was found to consist, at 1,550° C, of a continuous solid-solution series. These solid solutions may be effectively stabilized by quenching in air. Slow cooling, however, results in an unmixing reaction in the compositions in the central portion of the system. The results of the tests are given in table 6. These results are in general agreement with those of Schusterius [4].

TABLE 6. X-ray data for the SnO₂-TiO₂ system ^a

Mole ratio		Composition by weight		a	c	c/a ratio
SnO ₂	TiO ₂	SnO ₂	TiO ₂			
		%	%	A	A	
1	0	100	0	4.738	3.185	0.6772
4	1	88.30	11.70	4.710	3.143	.6673
2	b 1	79.05	20.96	4.692	3.130	.6672
1	b 1	65.35	34.65	4.664	3.065	.6572
1	b 2	48.54	51.47	4.644	3.029	.6522
1	4	32.04	67.96	4.624	3.001	.6491
0	1	0	100	4.592	2.959	.6444

^a Each sample had been fired to 1,550° C for at least 3 hours before cooling and conducting a petrographic and X-ray examination.

^b An unmixing reaction occurred on slow cooling of these samples. The unmixing was prevented by quenching in air from the high temperature.

3.2. Ternary Systems

a. MgO-CaO-TiO₂

A total of 42 compositions were prepared in this system for studies of phase relations and of dielectric properties. Of these, 18 selected samples were used in the determination of the compatibility relations. These samples were subjected to suitable heat treatment and subsequently analyzed by X-ray or petrographic methods. The results of these tests are given in table 7, and the composition triangles are shown in figure 1. Of the various possible binary joins in the ternary system, the following exist in the subsolidus diagram:³

MT₂-CT, MT-CT, M₂T-CT, MgO-CT, and

MgO-C₃T₂.

³ M=MgO, C=CaO, T=TiO₂, S=SnO₂. Thus, the formula 3CaO·2TiO₂ is shortened to C₃T₂.

It should be noted that the results (table 8) indicate little or no solid-solution formation in this system, with the probable exception of the areas adjacent to the compound C_3T_2 . This compound was found to undergo marked changes in structure with only very small quantities of impurities entering its lattice. These changes are discussed in a later portion of this report.

TABLE 7. Results of X-ray and petrographic study of selected compositions in the system MgO - CaO - TiO_2

Mole ratio M:C:T	Binary join or ternary field	Heat treatment		Phases identified
		Time	Temperature	
		hr	°C	
4:1:9	MT ₂ -CT	1	a 1,550	MT ₂ +CT.
1:4:6	do	1	1,550	Do.
4:1:5	MT-CT	1	1,550	MT+CT.
1:2:3	do	4	b 1,475	Do.
1:5:6	do	1	1,550	Do.
6:1:4	M ₂ T-CT	1	1,550	M ₂ T+CT.
2:7:8	do	1	1,550	Do.
1:3:3	MgO-CT	1	1,740	MgO+CT.
18:3:2	MgO-C ₃ T ₂	2.5	1,550	c MgO+C ₃ T ₂ .
1:3:2	do	1	1,645	Do.
2:27:18	do	2	>1,600	c C ₃ T ₂ +trace CaO.
1:1:5	MT ₂ -CT-TiO ₂	1	b 1,450	MT ₂ +CT+TiO ₂ .
3:2:6	MT ₂ -MT-CT	1	a 1,550	MT ₂ +MT+CT.
4:1:4	MT-M ₂ T-CT	1	a 1,590	MT+M ₂ T+CT.
4:1:2	MgO-M ₂ T-CT	---	a 1,672	MgO+M ₂ T+CT.
1:5:4	MgO-CT-C ₃ T ₂	---	1,645	d MgO+CT+C ₃ T ₂ .
2:2:1	MgO-CaO-C ₃ T ₂	1	1,645	e MgO+CaO+C ₃ T ₂ .
2:3:1	do	1	1,645	Do.

a The sample had fused at the temperature indicated.

b The sample was quenched from the temperature indicated.

c The results indicate the possibility of a small amount of solid solution in the areas adjacent to the compound C_3T_2 .

d Interpretation of powder patterns is difficult in this area due to the overlapping of some of the lines of CT and C_3T_2 . The results indicate that there may be a small amount of solid solution in the areas adjacent to the compound C_3T_2 .

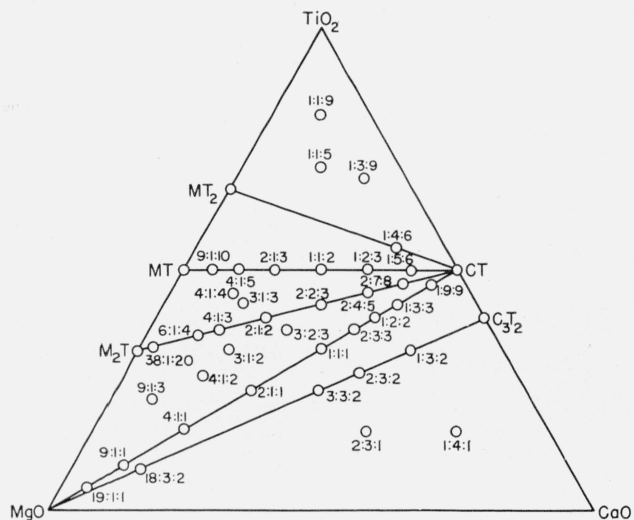


FIGURE 1. Compatibility relations in the system MgO - CaO - TiO_2 . The compositions are indicated by numbers and placed graphically according to mole ratios.

b. MgO - CaO - SnO_2

Sixteen compositions in this system have been prepared for study of solid-state reaction and dielectric properties. Nine of these compositions were selected for a preliminary study of compatibility relations in the system. The specimens were quenched from 1,550° C and analyzed by X-ray methods. The results obtained are listed in table 8. Because the results indicated that there is little or no solid-solution development, and that there are no ternary compounds, these nine tests were sufficient to establish the binary joins existing, which are: M_2S - CS , MgO - CS , and MgO - C_2S . The arrangement of compatibility triangles is shown in figure 2.

TABLE 8. Results of X-ray diffraction studies of specimens in the MgO - CaO - SnO_2 system

Mole ratio M:C:S	Binary join or ternary field	Heat treatment ^a		Phases identified
		Time	Temperature	
		hr	°C	
2:1:2	M_2S - CS	3	1,550	M_2S + CS .
1:1:1	MgO - CS	3	1,550	MgO + CS .
2:1:1	do	3	1,550	Do.
2:2:1	MgO - C_2S	3	1,550	MgO + C_2S .
1:1:2	M_2S - CS - SnO_2	3	1,550	M_2S + CS + SnO_2 .
1:1:4	do	3	1,550	Do.
3:1:2	MgO - M_2S - CS	3	1,550	MgO + M_2S + CS .
1:3:2	MgO - C_2S - CS	3	1,550	MgO + C_2S + CS .
2:4:1	MgO - CaO - C_2S	3	1,550	MgO + CaO + C_2S .

^a Each sample had been previously calcined for 4 hours at 1,100° C. Each specimen was quenched in air from the temperature indicated

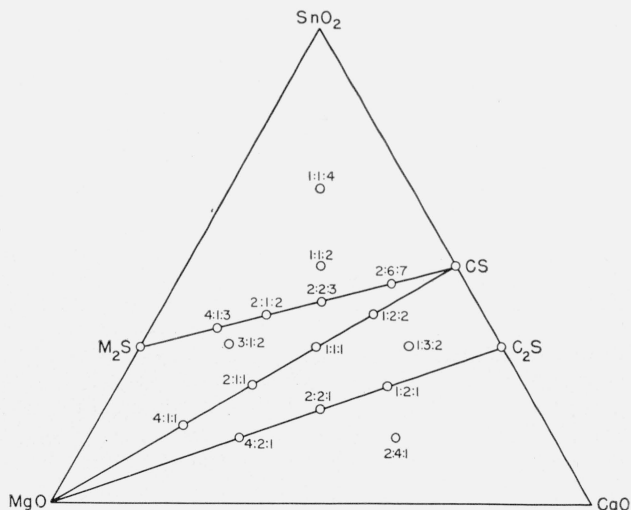


FIGURE 2. Compatibility relations in the system MgO - CaO - SnO_2 .

The compositions are indicated by numbers and placed graphically according to mole ratios. The compound MgO - SnO_2 is not indicated as it decomposes between 800° and 1,000° C, and the specimens studied here were all heated to 1,550° C.

Twenty compositions in the ternary field were given suitable heat treatment and, after cooling or quenching, were analyzed by X-ray and petrographic methods. From the results of these tests, which are listed in table 9, the arrangement of composition triangles was determined. An estimate of the solid-solution areas in the system was also obtained from these results.

TABLE 9. Results of X-ray diffraction study of specimens in the MgO-SnO₂-TiO₂ system

Mole ratio M:S:T	Binary join or ternary field	Heat treatment ^a		Phases identified (ss=solid solution)
		Time	Temperature	
		hr	°C	
2:1:1		3	1,550	M ₂ ST (single phase).
1:1:2	MT ₂ -SnO ₂	3	1,550	MT ₂ ss+SnO ₂ ss.
1:4:2	do	3	1,550	Do.
3:1:3 ^b	MT ₂ -M ₂ ST			Equilibrium conditions could not be obtained.
3:1:2	MT-M ₂ ST	3	1,550	(MT-M ₂ ST) ss.
5:1:4	do	3	1,550	(MT-M ₂ ST) ss+trace M ₂ S.
3:1:1	MT-M ₂ S	2.5	1,550	MT ss+M ₂ S ss.
6:1:4	do	16	1,300	Do.
4:1:2	do	15	1,400	None equilibrium.
4:1:1	M ₂ T-M ₂ S	3.5	1,550	(M ₂ T-M ₂ S) ss+trace MgO.
4:2:1	M ₂ S-M ₂ ST	3	1,550	M ₂ S ss+M ₂ ST ss.
2:3:1	M ₂ ST-SnO ₂	3	1,550	M ₂ ST+SnO ₂ ss.
1:1:4	MT ₂ -SnO ₂ -TiO ₂	15	1,400	MT ₂ ss+(SnO ₂ -TiO ₂) ss.
6:1:6	MT ₂ -MT-M ₂ ST	1	1,550	MT ₂ ss+(MT-M ₂ ST) ss.
1:1:1	MT ₂ -M ₂ ST-SnO ₂	2.5	1,550	MT ₂ ss+M ₂ ST+SnO ₂ ss.
2:1:2	do	3	1,550	Do.
3:2:1	M ₂ S-M ₂ ST-SnO ₂	2.5	1,550	M ₂ S ss+M ₂ ST ss+SnO ₂ .
8:1:4	M ₂ T-MT-M ₂ S	2.5	1,550	(M ₂ S-M ₂ T) ss+MT ss.
6:2:3	M ₂ S-MT-M ₂ ST	3	1,550	M ₂ S ss+(MT-M ₂ ST) ss.
6:1:1	MgO-M ₂ S-M ₂ T	3	1,550	MgO+(M ₂ S-M ₂ T) ss.

^aEach sample had been previously calcined for 4 hours at 1,100° C.

^bThe specimen was slowly cooled. All others were quenched from the temperature indicated.

The compatibility relations and the location of the compositions studied are shown in figure 3. The estimated solid-solution limits are indicated in figure 4. Extensive solid-solution development is noted throughout the system. However, the solid-solution areas and limits shown are not considered located with a high degree of accuracy. In addition, it is highly probable that the limits would change with differing heat treatments.

There is indicated a ternary compound having the probable formula 2MgO·SnO₂·TiO₂ or M₂ST. This compound is of the ilmenite type, is isostructural with the compound MgO·TiO₂, and forms a continuous series of solid solutions with it. The fact that all compositions on the MT-M₂ST join consist of a single phase and show a regular variation in lattice

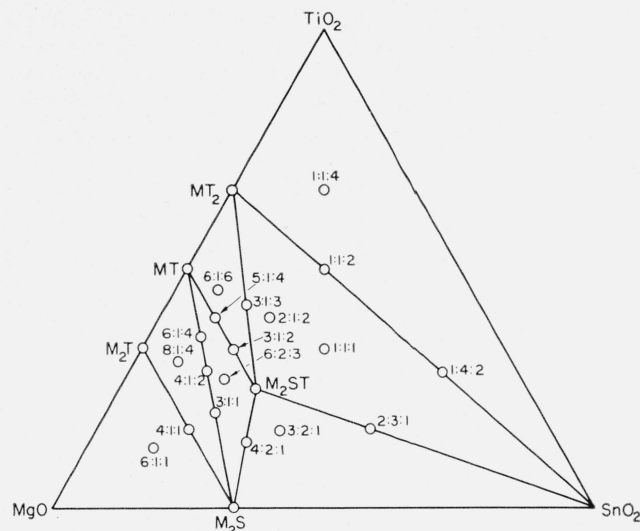


FIGURE 3. Compatibility relations in the system MgO-SnO₂-TiO₂.

The compositions are indicated by numbers and placed graphically according to mole ratios. All specimens were heated to 1,300° C or higher. Since the compound MgO·SnO₂ decomposes at a much lower temperature, it is not indicated on the diagram.

parameters and indices of refraction makes it quite difficult to establish unambiguously the formula of the ternary compound. The lattice parameters of the ternary composition M₂ST are $a=5.533$ Å, $\alpha=55.6^\circ$. An indexed powder pattern for this composition is included as table 10. The optical properties of this composition are: uniaxial negative, $\epsilon=1.85$, $\omega=2.07$.

TABLE 10. X-ray diffraction pattern of the compound 2MgO·SnO₂·TiO₂

hkl	1/d ² obs.	1/d ² calc.	R. I. ^a	hkl	1/d ² obs.	1/d ² calc.	R. I. ^a
111	0.046	0.046	90	122	.657	.655	3
010	.055	.055	75	341	.677	.677	4
110	.071	.071	41	442	.7103	.7115	7
121	.132	.132	100+	231	.7329	.7322	4
011	.151	.150	100++	240	.7848	.7845	5
222	.184	.184	8	352	.8605	.8616	8
120	.196	.196	62	251	.9679	.9777	5
111	.206	.205	6	141	1.0338	1.0324	6
220	.282	.282	29	151	1.0519	1.0510	9
232	.300	.300	17	041	1.0983	1.0966	4
231	.334	.334	73	440	1.1283	1.1278	6
021	.356	.355	4	451	1.1609	1.1618	6
121	.376	.371	8	250	1.1991	1.2011	13
124	.432	.432	31	150	1.2358	1.2347	15
121	.451	.450	60	033	1.3497	1.3508	19
030	.497	.496	7	142	1.3994	1.3968	7
242	.526	.527	4	361	1.4631	1.4620	7
343	.559	.561	18	242	1.4851	1.4826	3
022	.600	.600	13	664	1.5132	1.5093	6
141	.636	.634	3				

^a R. I. is the intensity of diffraction peaks relative to the strongest peak.

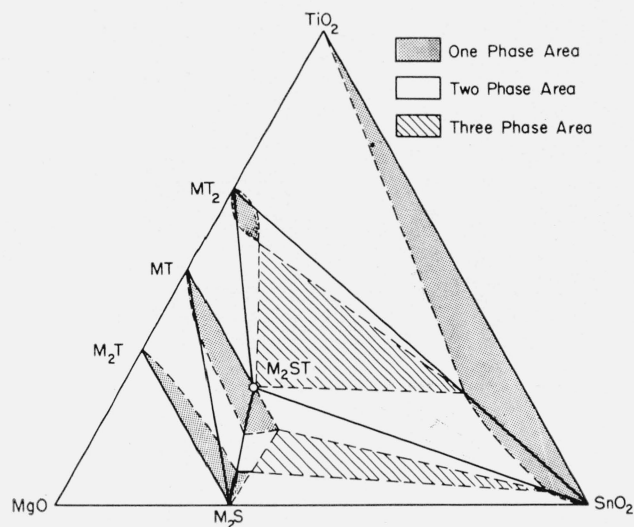


FIGURE 4. Estimated solid-solution areas in the system $\text{MgO-SnO}_2\text{-TiO}_2$.

The temperature range involved is between $1,300^\circ$ and $1,550^\circ \text{C}$.

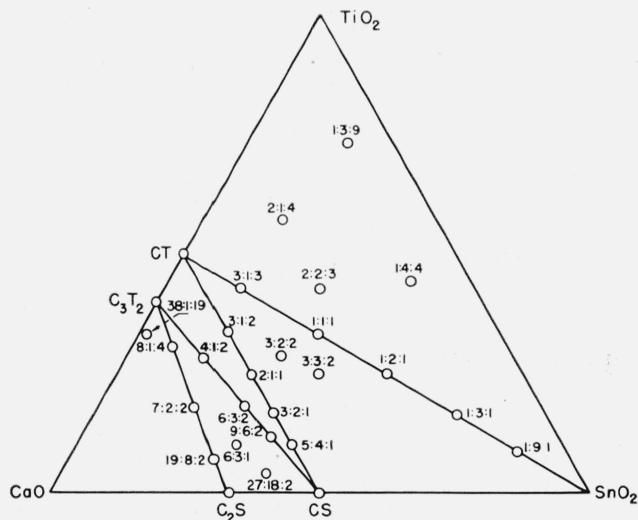


FIGURE 5. Compatibility relations in the system $\text{CaO-SnO}_2\text{-TiO}_2$.

The compositions are indicated by numbers and placed graphically according to mole ratios.

d. $\text{CaO-SnO}_2\text{-TiO}_2$

In this system, 22 selected ternary compositions were examined by X-ray methods after having been quenched from a temperature of $1,300^\circ$ to $1,550^\circ \text{C}$. Figure 5, showing the compatibility relations, was constructed from data in table 11. The binary joins are CT-SnO_2 , CT-CS , $\text{C}_3\text{T}_2\text{-CS}$, and $\text{C}_3\text{T}_2\text{-C}_2\text{S}$. Solid solutions were noted in all parts of the system. The estimated limits of the solid-solution areas are shown in figure 6.

In this case, as in that of the $\text{MgO-SnO}_2\text{-TiO}_2$ system, it is considered that the solid-solution limits are only approximate and that they would shift with heat treatments other than those used in this study.

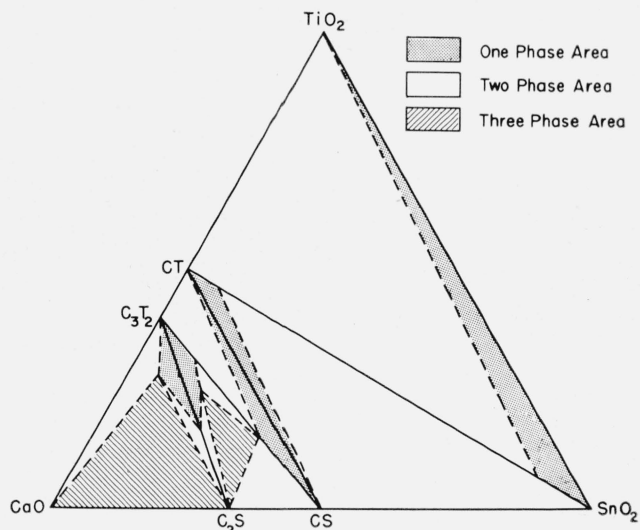


FIGURE 6. Estimated solid-solution areas in the system $\text{CaO-SnO}_2\text{-TiO}_2$.

The temperature range involved is between $1,300^\circ$ and $1,550^\circ \text{C}$.

TABLE 11. Results of X-ray study of selected compositions in the system $\text{CaO-SnO}_2\text{-TiO}_2$

Mole ratio $\text{C}_3\text{T}_2\text{:T}$	Binary join or ternary field	Heat treatment ^a		Phases identified (ss=solid solution)
		Time	Temperature	
		hr	$^\circ \text{C}$	
3:1:3	CT-SnO_2	2.5	1,550	$\text{CT ss} + \text{SnO}_2 \text{ ss.}$
1:1:1	do	3	1,550	Do.
1:3:1	do	2.5	1,550	Do.
1:9:1	do	3	1,550	Do.
3:1:2	CT-CS	3	1,550	$(\text{CT-CS}) \text{ ss.}$
3:2:1	do	3	1,550	Do.
4:1:2	$\text{C}_3\text{T}_2\text{-CS}$	3	1,550	$\text{CS ss} + \text{small amount}$
6:3:2	do	3	1,550	$\text{C}_3\text{T}_2 \text{ ss.}$
9:6:2	do	3	1,550	$\text{CS ss} + \text{trace C}_3\text{T}_2 \text{ ss.}$
8:1:4	$\text{C}_3\text{T}_2\text{-C}_2\text{S}$	3	1,550	CS ss.
7:2:2	do	3	1,550	$\text{C}_3\text{T}_2 \text{ ss.}$
19:8:2	do	3	1,550	Do.
1:1:4	$\text{CT-TiO}_2\text{-SnO}_2$	16	1,315	$\text{C}_3\text{T}_2 \text{ ss} + \text{C}_2\text{S.}$
1:3:9	do	3	1,400	$\text{CT ss} + (\text{TiO}_2\text{-SnO}_2) \text{ ss.}$
3:2:2	CT-CS-SnO_2	3	1,550	Do.
4:4:1	do	3	1,550	$(\text{CT-CS}) \text{ ss} + \text{SnO}_2 \text{ ss.}$
7:2:4	$\text{C}_3\text{T}_2\text{-CT-CS}$	3	1,550	Do.
3:1:1	$\text{C}_3\text{T}_2\text{-CS-C}_2\text{S}$	3	1,550	$\text{C}_3\text{T}_2 \text{ ss} + (\text{CT-CS}) \text{ ss.}$
9:6:1	do	3	1,550	$\text{CS ss} + \text{C}_2\text{S} + \text{C}_3\text{T}_2 \text{ ss.}$
27:18:2	do	3	1,550	$\text{CS ss} + \text{C}_2\text{S.}$
4:1:1	$\text{C}_3\text{T}_2\text{-C}_2\text{S-CaO}$	3	1,550	Do.
38:1:19	do	3	1,550	$\text{CaO} + \text{C}_2\text{S} + \text{C}_3\text{T}_2 \text{ ss.}$
				$\text{CaO} + \text{C}_3\text{T}_2 \text{ ss.}$

^a Each sample had been previously calcined for 4 hours at $1,000^\circ$ to $1,100^\circ \text{C}$. Each specimen was quenched from the temperature indicated.

3.3. The System $\text{MgO-CaO-SnO}_2\text{-TiO}_2$

In addition to the 19 binary joins established in the four subsidiary ternary systems, there are 13 possible binary joins across the interior of the quaternary tetrahedron. Investigation of 10 selected quaternary compositions (with the preliminary assumption that there are no quaternary compounds present) indicated that only 2 of these binary joins

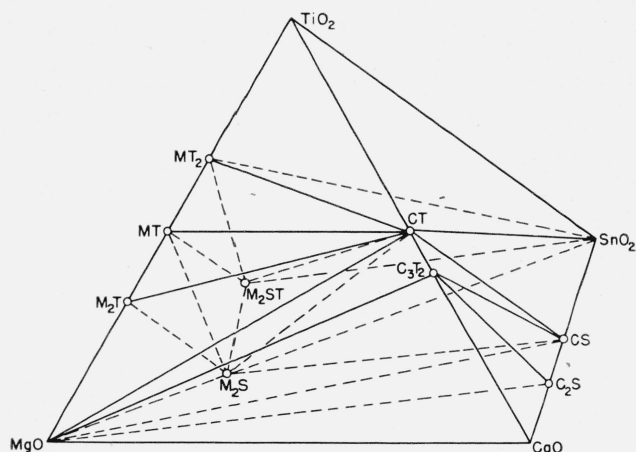


FIGURE 7. Compatibility relations in the system MgO-CaO-SnO₂-TiO₂.

No attempt has been made to indicate the extensive solid-solution development that occurs in this system.

are valid. They are the M₂S-CT and M₂ST-CT joins. The quaternary system could then be divided into 12 subsystems or tetrahedra. In order to verify the initial assumption as to the lack of quaternary

TABLE 12. Results of X-ray diffraction studies of specimens in the MgO-CaO-SnO₂-TiO₂ system

Mole ratio M:C:S:T	Binary join, join plane, or quaternary volume	Heat treatment ^a		Phases identified (ss=solid solution)
		Time	Temperature	
2:1:1:1...	M ₂ S-CT	3 hr	1,550 °C	M ₂ S ss+CT ss.
2:3:1:3...	do	3	1,550	Do.
2:2:1:2...	do	3	1,550	Do.
2:1:1:2...	M ₂ ST-CT	3	1,550	M ₂ ST ss+CT.
3:4:3:1...	MgO-CT-CS	6	1,550	MgO+(CT-CS) ss.
2:4:4:1...	M ₂ S-CT-CS	3	1,550	M ₂ S ss+(CT-CS) ss.
2:2:2:1...	do	3	1,550	Do.
3:1:1:2...	M ₂ S-MT-CT	3	1,400	M ₂ S ss+MT ss+CT.
1:2:1:2...	M ₂ S-CT-SnO ₂	3	1,450	M ₂ S ss+CT ss+SnO ₂ ss.
2:1:2:1...	do	3	1,400	Do.
1:6:1:2...	MgO-CaO-C ₂ S-C ₃ T ₂	3	1,550	C ₃ T ₂ ss+CaO+MgO.
1:1:2:4...	M ₂ S-M ₂ T-MT-CT	3	1,400	C ₃ T ₂ ss+CaO.
1:15:4:4...	do	3	1,400	Do.
1:6:2:2...	MgO-C ₂ S-CS-C ₃ T ₂	3	1,550	C ₃ T ₂ ss+CS ss+MgO
5:1:1:2...	MgO-M ₂ S-M ₂ T-CT.	3	1,550	(M ₂ T-M ₂ S) ss+CT+MgO.
1:5:1:3...	MgO-CS-CT-C ₃ T ₂	3	1,550	C ₃ T ₂ ss+(CT-CS) ss+MgO.
6:2:2:1...	MgO-M ₂ S-CS-CT	3	1,550	MgO+M ₂ S+(CT-CS) ss.
5:1:1:3...	M ₂ S-M ₂ T-MT-CT	3	1,400	(M ₂ S-M ₂ T) ss+MT ss+CT.
5:1:2:3...	M ₂ S-M ₂ ST-MT-CT.	3	1,400	M ₂ S ss+(M ₂ ST-MT) ss+CT.
4:1:3:2...	M ₂ S-M ₂ ST-CT-SnO ₂	3	1,450	M ₂ S ss+M ₂ ST+CT ss+SnO ₂ .
2:2:3:1...	M ₂ S-CS-CT-SnO ₂	3	1,550	M ₂ S ss+(CT-CS) ss+SnO ₂ .
1:1:1:2...	M ₂ ST-MT ₂ -CT-SnO ₂	3	1,550	MT ₂ ss+M ₂ ST ss+CT+SnO ₂ ss.
4:1:1:5...	M ₂ ST-MT-MT ₂ -CT.	5	1,400	(M ₂ ST-MT) ss+MT ₂ ss+CT.
1:1:1:4...	MT ₂ -CT-TiO ₂ -SnO ₂	4	1,350	MT ₂ +CT+TiO ₂ ss+SnO ₂ ss.

^a Each sample had been previously calcined for 4 hours at 1,000° to 1,100° C. Each specimen was quenched from the temperature indicated.

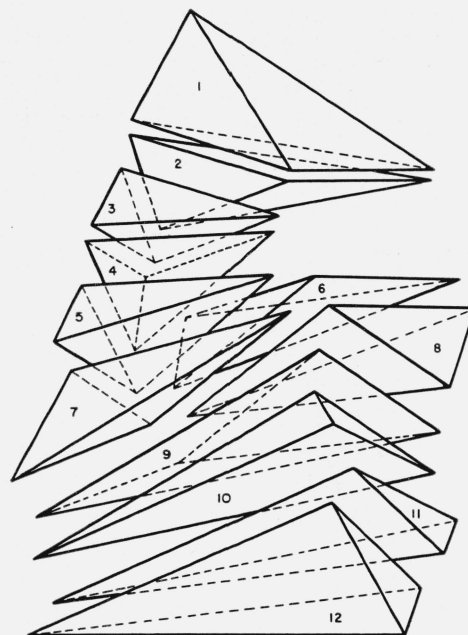


FIGURE 8. An "expanded" version of figure 7.

No.	End members of the 12 subtetrahedra of the system MgO-CaO-SnO ₂ -TiO ₂
1.....	MT ₂ -CT-TiO ₂ -SnO ₂ .
2.....	MT ₂ -M ₂ ST-CT-SnO ₂ .
3.....	MT ₂ -MT-M ₂ ST-CT.
4.....	MT-M ₂ S-M ₂ ST-CT.
5.....	MT-M ₂ T-M ₂ S-CT.
6.....	M ₂ S-M ₂ ST-CT-SnO ₂ .
7.....	MgO-M ₂ T-M ₂ S-CT.
8.....	M ₂ S-CT-CS-SnO ₂ .
9.....	MgO-M ₂ S-CS-CT.
10.....	MgO-CS-CT-C ₃ T ₂ .
11.....	MgO-C ₂ S-CS-C ₃ T ₂ .
12.....	MgO-CaO-C ₂ S-C ₃ T ₂ .

compounds, at least one composition in the interior of each of the subtetrahedra was studied. In each case the expected phases were identified, and no indication of the presence of any quaternary compound was obtained. Solid-solution development was observed in all of the quaternary compositions. The results of the tests on quaternary samples are given in table 12. The arrangement of composition tetrahedra is illustrated in figures 7 and 8, in which no attempt has been made to indicate solid solutions.

4. Results of Dielectric Testing

4.1. The System MgO-CaO-TiO₂

The circles in figure 1 represent compositions which were formed into appropriate specimens and tested for their dielectric properties. The results of these tests are listed in tables 13, 14, and 15. The maturing temperatures were found to be high,

TABLE 13. Results of dielectric testing

Mole ratio	Binary join, ternary field, or quaternary volume	Heat treatment ^a		Shrink- age	Absorp- tion	Dielectric constant, K , at 25° C and—			Reciprocal, Q , of power factor at 25° C and—		
		Time	Temper- ature			50 kc	1 Mc	20 Mc	50 kc	1 Mc	20 Mc
M:C:T											
The system MgO-CaO-TiO ₂											
4:1:5	MT-CT	1	1,500	14.5	0.00	35.1	35.1	35.0	1,100	3,000	3,000
2:1:3	do	1	1,500	11.4	.13	54.1	54.1	54.1	900	9,000	1,400
1:1:2	do	1	1,500	14.0	.06	78.6	78.5	78.1	10,000	10,000	700
1:2:3	do	2	1,500	12.6	.06	110	100	108	3,000	9,000	6,000
1:5:6	do	1	1,500	16.6	.02	144	143	145	10,000	10,000	3,000
38:1:20	M ₂ T-CT	1	1,550	14.3	.02	18.0	17.8	17.3	4,000	2,000	8,000
6:1:4	do	2	1,550	16.0	.01	31.6	31.6	31.6	10,000	10,000	2,000
4:1:3	do	1	1,540	13.8	.19	38.0	38.0	37.6	1,100	6,000	1,300
2:1:2	do	1	1,550	11.8	.00	60.6	60.6	60.6	10,000	10,000	2,000
2:2:3	do	1	1,550	12.7	.05	92.9	92.7	92.7	9,000	7,000	700
2:4:5	do	1	1,550	16.0	.00	122	121	122	4,000	10,000	7,000
2:7:8	do	1	1,550	17.9	.17	135	135	135	6,000	9,000	10,000
9:1:1	MgO-CT	1	1,725	15.1	.13	23.6	23.6	23.6	3,000	10,000	5,000
4:1:1	do	1	1,725	14.7	.07	43	43	43	3,000	10,000	1,500
2:1:1	do	1	1,725	15.4	.07	73	73	73	2,500	6,000	900
2:1:1 ^b	do	1	1,500	13.5	.00	69	69	69	3,000	4,000	510
1:1:1	do	1	1,725	14.0	.04	98	98	98	4,000	7,000	600
2:3:3	do	1	1,730	14.0	.00	119	118	118	4,000	8,000	3,000
2:3:3 ^c	do	1	1,500	12.2	.10	106	106	106	1,000	5,000	1,000
2:3:3 ^b	do	1	1,500	13.2	.00	109	109	109	1,000	4,000	2,000
1:2:2	do	1	1,725	14.7	.12	128	126	126	7,000	7,000	7,000
1:3:3	do	1	1,730	14.4	.02	153	153	152	2,400	3,600	5,000
1:3:3 ^b	do	1	1,500	13.4	.00	129	129	129	1,000	5,000	1,000
18:3:2	MgO-C ₃ T ₂	1/2	1,625	15.8	.10	15.2	16.9	17.2	400	3,800	2,600
3:3:2	do	1/2	1,625	15.8	.05	40.5	39.4	39.4	900	1,700	1,000
2:3:2	do	1/2	1,650	16.0	.26	42.8	42.8	41.6	1,300	1,300	1,800
1:3:2	do	1/2	1,650	15.6	.22	47.0	47.2	45.9	1,100	2,100	1,700
1:1:5	MT ₂ -CT-TiO ₂	1	1,350	16.0	.06	67	66	66	800	1,200	2,000
1:1:9	do	1	1,350	17.3	.20	94	92	90	44	126	440
1:3:9	do	1	1,350	17.3	.01	109	106	105	86	230	1,500
3:1:3	MT-M ₂ T-CT	2	1,500	12.2	.18	44	43	43	1,300	10,000	2,400
4:1:4	do	2	1,500	12.3	.06	37	37	37	10,000	1,000	2,000
9:1:3	M ₂ T-MgO-CT	1	1,540	10.2	.10	24	24	24	4,000	10,000	2,700
4:1:2	do	1	1,550	12.4	.10	41	40	40	1,500	10,000	2,600
3:1:2	do	2	1,550	11.9	.09	52	52	51	10,000	10,000	2,100
3:2:3	do	1	1,550	12.0	.13	77	77	76	6,000	10,000	700
2:3:1	MgO-C ₃ T ₂ -CaO	1/2	1,625	20.0	.06	26	28	28	300	1,600	1,400
1:4:1	do	1/2	1,650	21.0	.00	30	29	27	600	2,000	1,900
M:C:S											
The system MgO-CaO-SnO ₂											
2:1:2 ^d	M ₂ S-CS	1	1,550	18.0	0.15	11.0	10.8	10.7	1,100	770	410
2:6:7	do	1	1,550	19.5	.26	14.1	14.0	14.0	190	670	620
4:1:1	MgO-CS	1	1,550	19.5	.01	14.0	14.0	14.0	4,000	10,000	2,000
2:1:1	do	1	1,550	21.0	.03	13.2	13.2	13.2	2,000	10,000	2,000
1:1:1	do	1	1,550	21.0	.02	14.3	14.3	14.3	3,000	10,000	1,000
1:2:2	do	1	1,550	22.2	.02	14.4	14.4	14.4	3,000	10,000	4,000
4:2:1 ^d	MgO-C ₂ S	1	1,550	20.1	.00	11.2	11.0	11.0	300	230	360
2:2:1	do	1	1,550	19.0	.41	10.6	10.6	10.6	500	850	600
1:2:1 ^d	do	1	1,550	21.5	.00	13.4	13.4	13.4	200	760	760
C:S:T											
The system CaO-SnO ₂ -TiO ₂											
3:1:3	CT-SnO ₂	1	1,500	16.8	0.01	106	106	106	600	2,000	1,500
1:3:1	do	1	1,550	19.7	.12	39	39	38	30	170	230
1:9:1 ^d	do	1	1,550	18.0	.16	27	25	---	40	30	---
3:1:2	CT-CS	1	1,500	17.9	.00	84	84	84	2,800	5,000	800
2:1:1	do	1	1,550	17.8	.15	62	61	61	850	5,000	2,100
3:2:1	do	1	1,550	16.8	.02	38	38	37	2,000	4,000	2,000
5:4:1	do	1	1,500	19.9	.00	24	24	24	1,500	2,000	2,000
4:1:2 ^d	C ₃ T ₂ -CS	1	1,550	21.0	.12	45.2	44.9	---	210	470	---
6:3:2 ^d	do	1/2	1,550	22.0	.02	37.8	37.6	37.4	290	600	380
9:6:2	do	1	1,500	21.5	.08	30.6	30.6	30.6	7,000	10,000	760
8:1:4 ^d	C ₃ T ₂ -C ₂ S	1	1,550	21.7	.05	42	42	---	90	400	---
7:2:2 ^d	do	1	1,550	23.7	.08	35	34	35	55	70	170
19:8:2 ^d	do	1	1,550	22.9	.02	18	18	18	70	230	460
1:3:9	CT-SnO ₂ -TiO ₂	1	1,430	15.0	.02	76	76	76	200	1,300	680
2:1:4	do	1	1,500	16.8	.09	111	110	110	2,000	3,000	2,200
2:2:3	do	1	1,500	15.0	.00	82	81	81	1,700	2,300	2,400
3:3:2	CT-CS-SnO ₂	1	1,500	17.0	.16	62	59	59	400	1,500	1,600
3:2:2 ^d	do	1	1,550	16.3	.04	67	67	67	1,000	2,000	440
27:18:2 ^d	C ₃ T ₂ -CS-C ₂ S	1	1,550	23.1	.00	17.5	17.3	17.3	150	320	340
6:3:1 ^d	do	1	1,550	23.5	.00	23.7	23.5	23.5	220	470	400

See footnotes at end of table.

TABLE 13. *Results of dielectric testing—Continued*

Mole ratio	Binary join, ternary field, or quaternary volume	Heat treatment ^a		Shrink- age	Absorp- tion	Dielectric constant, <i>K</i> , at 25° C and—			Reciprocal, <i>O</i> , of power factor at 25° C and—		
		Time	Temper- ature			50 kc	1 Mc	20 Mc	50 kc	1 Mc	20 Mc
M:C:S:T		The system MgO-CaO-SnO ₂ -TiO ₂									
8:1:4:1 ^b	M ₂ S-CT	1	1,500	----	0.18	14.8	14.7	14.7	2,000	7,000	2,000
4:1:2:1 ^b	do	1	1,500	20.2	.43	17.4	17.4	17.4	2,000	4,000	3,000
2:1:1:1	do	1	1,550	16.4	.34	29.6	29.6	29.6	3,000	7,000	4,000
2:2:1:2	do	1	1,550	13.9	.23	53.1	53.0	52.9	5,000	5,000	2,000
2:3:1:3 ^d	do	1	1,550	15.0	.13	68.1	68.0	68.0	2,000	6,000	800
2:5:1:5 ^b	do	1	1,500	13.4	.16	102	102	102	1,000	4,000	2,000
2:9:1:9 ^b	do	1	1,500	12.8	.26	118	118	118	180	250	1,000
2:1:1:2	M ₂ ST-CT	1	1,450	14.0	.17	32.8	32.6	32.6	2,000	4,000	1,800
2:2:1:3	do	1	1,450	12.8	.05	56.0	56.0	56.0	3,000	1,700	560
2:9:1:10 ^b	do	1	1,500	11.8	.00	109	109	108	1,000	3,000	2,000
1:3:1:2 ^b	MgO-CT-CS	1	1,500	17.1	.05	72.7	72.7	72.7	7,000	4,000	500
2:2:1:1	do	1	1,550	16.8	.12	33.7	33.7	33.7	3,000	3,000	2,000
3:4:3:1	do	1	1,550	14.3	.23	22.1	22.1	22.1	3,000	6,000	1,000
2:5:4:1	do	1	1,550	19.3	.05	22.3	22.2	22.2	2,000	5,000	700
2:2:2:1	M ₂ S-CT-CS	1	1,550	19.4	.12	27.7	27.6	27.5	420	5,000	640
3:1:1:2	M ₂ S-MT-CT	1	1,400	11.5	.30	27.6	27.4	27.4	1,000	4,000	1,500
5:1:2:3	MT-M ₂ S-M ₂ ST-CT	1	1,450	11.6	.66	23.7	23.6	23.6	40	560	800
5:1:1:3	MT-M ₂ T-M ₂ S-CT	1	1,450	10.4	.10	24.0	23.9	23.9	3,000	4,000	5,000
5:1:1:2	MgO-M ₂ T-M ₂ S-CT	1	1,550	14.2	.40	27.2	27.1	27.0	4,000	7,000	580
4:3:2:2	MgO-M ₂ S-CS-CT	1	1,550	16.3	.44	41.5	41.4	41.4	3,000	4,500	1,300
1:5:1:3	MgO-CS-CT-C ₃ T ₂	1	1,550	22.5	.35	45.8	45.8	45.3	140	280	500
1:6:2:2	MgO-C ₂ S-CS-C ₃ T ₂	1	1,550	17.8	.29	34.4	34.2	34.1	500	500	330
1:6:1:2 ^b	MgO-CaO-C ₂ S-C ₃ T ₂	1	1,500	22.2	.18	37.3	37.3	37.1	430	900	380
1:15:4:4	do	1	1,500	22.6	.04	30.6	30.2	29.7	90	130	280

^a Each specimen had been calcined once prior to the recorded heat treatment.

^b A commercial grade of $\text{CaO} \cdot \text{TiO}_2$ was used in the preparation of this specimen.

^c Periclase of 96-percent purity was used in the preparation of this specimen.

^d One percent of Fe_2O_3 was added to the specimen.

TABLE 14. *Variation of dielectric constant with temperature*

Mole ratio	Binary join, ternary field, or quaternary volume	Value of K at 1 Me and—												Average temperature coefficient of K over range indicated
		−50° C	0° C	25° C	50° C	75° C	100° C	125° C	150° C	175° C	200° C	225° C	250° C	
M:C:T	The system MgO-CaO-TiO ₂													
9:1:10	MT-CT	24.1	23.9	23.7	23.5	23.4	23.4	23.3	23.3	23.2	23.2	23.2	23.2	$ppm/^{\circ}C$ −130
4:1:5	do	38.9	37.6	37.1	36.4	35.8	35.3	34.9	34.5	34.1	33.8	33.5	33.3	−520
2:1:3	do	58.5	55.3	54.1	52.7	51.5	50.3	49.4	48.6	47.8	47.0	46.4	45.9	−800
1:1:2	do	87.1	81.9	78.5	75.2	72.7	70.5	68.3	66.6	65.2	63.7	62.5	61.4	−1,080
38:1:20	M ₂ T-CT	---	---	17.7	17.7	17.7	17.7	17.7	17.7	17.8	17.8	17.8	18.2	+280
6:1:4	do	33.1	32.5	32.0	31.6	31.0	30.6	30.2	29.8	29.4	29.1	28.9	28.7	−480
2:1:2	do	66.8	62.4	60.6	58.2	56.4	54.7	53.2	52.0	50.9	49.8	48.9	48.2	−1,100
2:2:3	do	104	97.6	92.7	88.6	85.4	82.4	79.8	77.7	75.6	73.4	72.0	70.1	−1,300
2:7:8	do	151	141	135	128	123	119	114	111	107	104	102	100	−1,360
4:1:1	MgO-CT	46.1	44.3	43.1	42.0	41.0	40.2	39.4	38.8	38.2	37.8	37.3	37.1	−720
2:1:1	do	79.5	74.5	72.7	70.2	68.2	66.3	64.7	63.3	62.0	60.9	60.1	(^a)	−1,010
2:1:1 b	do	77	72	69	67	65	64	62	61	60	59	58	57	−1,000
1:1:1	do	108	100	97.6	93.7	90.4	87.6	84.9	82.9	80.8	78.9	77.7	(^a)	−1,090
2:3:3 b	do	123	113	109	106	103	100	97	95	92	91	89	88	−1,100
1:2:2	do	142	133	128	123	119	115	112	109	106	104	102	(^a)	−1,190
1:3:3 b	do	146	135	129	125	121	117	114	111	108	106	103	102	−1,180
18:3:2	MgO-C ₃ T ₂	18.4	17.4	17.4	17.3	17.3	17.3	17.3	17.4	17.5	17.6	17.7	(^a)	-----
2:3:2	do	45.4	44.8	44.6	44.5	43.8	43.6	43.4	43.2	43.1	43.3	43.5	(^a)	-----
1:3:9	MT ₂ -CT-TiO ₂	122	114	111	108	105	103	100	97.6	95.5	93.4	91.6	89.6	−1,020
4:1:4	MT-M ₂ T-CT	38.8	37.7	36.9	36.2	35.7	35.1	34.6	34.3	33.9	33.5	33.2	33.0	−540
3:2:3	M ₂ T-MgO-CT	84.4	80.4	76.7	73.4	71.0	68.9	66.8	65.0	63.0	62.2	61.2	59.9	−1,130
2:3:1	MgO-C ₃ T ₂ -CaO	31.0	30.8	30.7	30.8	30.7	30.6	30.6	30.6	30.7	30.8	31.1	(^a)	-----
1:4:1	do	29.3	29.2	29.1	29.0	28.9	28.9	28.9	29.0	29.2	29.4	(^a)	-----	-----

See footnotes at end of table.

TABLE 14. Variation of dielectric constant with temperature—Continued

Mole ratio	Binary join, ternary field, or quaternary volume	Value of K at 1 Mc and—													Average temperature coefficient of K over range indicated
		−50° C	0° C	25° C	50° C	75° C	100° C	125° C	150° C	175° C	200° C	225° C	250° C		
M:C:S		The system MgO-CaO-SnO ₂													
2:6:7	M ₂ S-CS	13.7	13.9	13.9	14.0	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.2	+120	
4:1:1	MgO-CS	13.9	14.0	14.0	14.0	14.2	14.3	14.3	14.3	14.4	14.4	14.4	14.5	+140	
2:1:1	do	13.2	13.2	13.3	13.3	13.3	13.3	13.3	13.4	13.4	13.5	13.5	13.6	+100	
1:1:1	do	14.2	14.3	14.3	14.4	14.4	14.5	14.5	14.5	14.6	14.6	14.7	14.7	+120	
1:1:1 ^e	do	14.2	14.3	14.3	14.4	14.4	14.4	14.4	14.5	14.5	14.5	14.6	14.7	+120	
1:2:2	do	14.3	14.3	14.3	14.4	14.4	14.4	14.4	14.5	14.5	14.6	14.7	14.7	+90	
4:2:1 ^e	MgO-C ₂ S	10.9	11.0	11.0	11.2	11.2	11.3	11.4	11.4	11.4	11.5	11.5	11.6	+210	
2:2:1	do	9.9	10.5	10.5	10.5	10.6	10.6	10.6	10.6	10.7	10.7	10.7	10.8	+290	
1:2:1 ^e	do	13.3	13.4	13.4	13.5	13.5	13.6	13.6	13.7	13.8	14.0	14.2	14.4	+260	
C:S:T		The system CaO-SnO ₂ -TiO ₂													
1:3:1	CT-SnO ₂	39.5	37.8	37.1	36.0	35.9	35.2	34.8	34.5	34.0	33.8	33.6	33.4	−550	
1:9:1 ^e	do	24.9	25.3	25.4	(^a)	---	---	---	---	---	---	---	---	---	
3:1:2	CT-CS	91	86	84	81	79	77	76	74	72	71	70	69	−920	
2:1:1	do	---	---	60.8	59.1	57.6	56.3	55.3	54.4	53.4	52.7	51.9	51.4	−750	
3:2:1	do	---	---	37.8	37.3	36.8	36.3	35.9	35.5	35.3	34.9	34.7	34.4	−420	
5:4:1	do	24.6	24.4	24.3	24.2	24.1	24.0	24.0	23.9	23.9	23.8	23.8	23.8	−110	
4:1:2 ^e	C ₃ T ₂ -CS	46.1	45.3	44.9	44.4	44.2	44.1	43.8	43.7	43.6	(^a)	---	---	−250	
6:3:2 ^e	do	38.6	37.9	37.6	37.1	36.9	36.7	36.5	36.5	36.4	36.4	(^a)	---	−240	
8:1:4 ^e	C ₃ T ₂ -C ₂ S	42.2	41.8	41.7	41.5	41.4	41.4	41.3	41.3	(^a)	---	---	---	−110	
7:2:2 ^e	do	35.0	34.9	34.9	(^a)	---	---	---	---	---	---	---	---	---	
19:8:2 ^e	do	17.6	17.7	17.7	17.8	17.9	18.1	18.3	(^a)	---	---	---	---	+220	
1:3:9	CT-SnO ₂ -TiO ₂	82	78	76	74	72	71	69	68	67	65	64	(^a)	−900	
2:2:3	do	---	---	81.2	78.6	76.5	74.3	72.7	71.2	69.3	68.0	66.7	65.2	−970	
2:1:4	do	---	---	110	107	103	99.5	97.1	94.7	92.0	90.0	88.4	86.0	−1,090	
3:2:2 ^e	CT-CS-SnO ₂	71.5	68.5	67.0	65.1	63.6	62.5	61.4	60.3	59.3	58.5	57.8	57.2	−740	
3:3:2	do	56.0	54.0	52.0	50.0	49.5	48.5	47.5	47.0	46.5	46.0	46.6	(^a)	−670	
27:18:2 ^e	C ₃ T ₂ -CS-C ₂ S	17.2	17.3	17.3	17.4	17.4	17.6	17.7	17.8	18.0	18.1	18.4	18.6	+260	
6:3:1 ^e	do	23.8	23.6	23.5	23.5	23.5	23.4	23.6	23.7	23.8	23.9	24.1	24.5	---	
M:C:S:T		The system MgO-CaO-SnO ₂ -TiO ₂													
8:1:4:1 ^b	M ₂ S-CT	15.0	14.8	14.7	14.6	14.5	14.4	14.4	14.3	14.3	14.3	14.3	14.2	−180	
4:1:2:1 ^b	do	18.0	17.5	17.4	17.3	17.1	16.9	16.8	16.8	16.7	16.6	16.5	16.5	−290	
2:1:1:1	do	32.0	30.4	29.6	29.1	28.4	27.9	27.5	27.0	26.6	26.3	26.0	25.8	−710	
2:2:1:2	do	59	55	53	52	50	49	48	47	46	45	44	43	−1,050	
2:5:1:5 ^b	do	116	106	102	99	96	93	90	88	84	83	82	81	−1,190	
2:9:1:9 ^b	do	135	124	118	113	110	106	103	101	98	96	94	92	−1,260	
2:1:1:2	M ₂ ST-CT	35.0	33.2	32.6	32.1	31.5	30.9	30.4	30.0	29.7	29.4	29.1	29.0	−625	
2:2:1:3	do	62	58	56	54	53	52	51	50	49	48	48	47	−925	
2:9:1:10 ^b	do	124	114	109	105	102	99	96	94	92	90	88	87	−1,210	
1:3:1:2 ^b	MgO-CT-CS	80	75	73	71	69	68	66	65	64	63	62	61	−890	
2:2:1:1 ^e	do	35.3	34.2	33.7	33.6	32.8	32.4	32.1	31.7	31.5	31.2	31.1	30.9	−445	
3:4:3:1	do	22.5	22.2	22.1	22.0	21.8	21.8	21.7	21.6	21.6	21.5	21.5	21.4	−200	
2:5:4:1	do	22.6	22.4	22.3	22.2	22.2	22.1	22.0	21.9	21.9	21.9	21.8	21.8	−110	
2:2:2:1	M ₂ S-CT-CS	29.1	28.1	27.6	27.2	26.8	26.4	26.1	25.8	25.6	25.4	25.3	24.9	−500	
3:1:1:2	M ₂ S-MT-CT	29.0	27.9	27.4	26.9	26.5	26.2	25.9	25.6	25.4	25.2	24.9	24.8	−620	
5:1:2:3	MT-M ₂ S-M ₂ ST-CT	24.6	24.2	23.9	23.6	23.4	23.2	23.1	22.9	22.8	22.7	22.6	22.5	−310	
5:1:1:3	MT-M ₂ T-M ₂ S-CT	25.2	24.3	23.9	23.6	23.3	23.1	22.9	22.6	22.5	22.3	22.2	22.0	−450	
5:1:1:2	MgO-M ₂ S-M ₂ T-CT	28.6	27.4	27.1	26.5	26.2	25.9	25.6	25.4	25.2	25.0	24.9	24.7	−500	
4:3:2:2	MgO-M ₂ S-CS-CT	45	42	41	40	39	38	38	37	37	36	36	35	−830	
1:5:1:3	MgO-CS-CT-C ₃ T ₂	47.4	46.3	45.8	45.4	45.1	44.8	(^a)	---	---	---	---	---	−370	
1:6:2:2	MgO-C ₂ S-CS-C ₃ T ₂	35.1	34.5	34.2	33.9	33.7	33.5	33.4	33.3	33.3	33.2	33.2	33.3	−180	
1:6:1:2	MgO-CaO-C ₂ S-C ₃ T ₂	38.7	37.9	37.3	36.8	36.5	36.2	36.0	35.8	35.7	35.6	35.5	(^a)	−340	
1:15:4:4	do	30.4	30.1	30.0	29.9	29.8	29.8	29.7	29.5	29.3	28.9	28.4	28.3	−240	

^a At and above the temperature indicated, the specimen behaved as a semiconductor.^b A commercial grade of CaO·TiO₂ was used in the preparation of the specimen.^c One percent of Fe₂O₃ was added to the specimen.

TABLE 15. Variation of Q value with temperature

Mole ratio	Binary join, ternary field, or quaternary volume	Value of Q at 1 Mc and—											
		−50° C	0° C	25° C	50° C	75° C	100° C	125° C	150° C	175° C	200° C	225° C	250° C
M:C:T		The system MgO-CaO-TiO ₂											
9:1:10	MT-CT	5,000	5,000	3,000	5,000	5,000	3,500	3,000	2,400	1,300	650	320	155
4:1:5	do	10,000	10,000	10,000	7,000	7,000	7,000	7,000	4,000	3,000	2,000	900	500
2:1:3	do	10,000	10,000	10,000	10,000	10,000	10,000	10,000	5,000	3,000	1,300	700	340
1:1:2	do	10,000	10,000	10,000	10,000	10,000	10,000	4,000	4,000	3,000	1,200	600	270
38:1:20	M ₂ T-CT			8,000	10,000	8,000	8,000	8,000	6,000	4,500	2,500	1,600	820
6:1:4	do	10,000	10,000	10,000	10,000	7,000	5,000	4,000	3,000	1,650	850	440	210
2:1:2	do	10,000	10,000	10,000	10,000	6,000	4,000	3,000	2,200	1,200	530	250	100
2:2:3	do	10,000	10,000	7,000	5,000	3,000	2,500	1,800	1,050	530	230	115	100
2:7:8	do	10,000	10,000	9,000	5,000	4,000	3,000	1,700	1,100	550	250	120	50
4:1:1	MgO-CT	10,000	10,000	10,000	6,000	3,000	2,300	1,300	700	330	160	75	30
2:1:1	do	6,000	6,000	6,000	4,000	3,000	1,700	1,000	500	260	110	60	(a)
2:1:1 ^b	do	2,300	2,600	4,000	2,000	1,900	1,900	1,800	980	590	400	190	100
1:1:1	do	7,000	7,000	7,000	4,000	3,000	1,700	900	500	230	104	55	(a)
2:3:3 ^b	do	910	2,500	2,300	2,300	2,200	2,200	2,100	1,030	1,000	400	160	90
1:2:2	do	7,000	7,000	7,000	3,000	2,400	1,400	800	420	230	103	48	(a)
1:3:3 ^b	do	1,800	1,800	2,300	2,200	2,200	2,100	2,000	990	550	380	160	80
18:3:2	MgO-C ₃ T ₂	3,000	3,000	2,070	1,670	1,120	510	420	260	150	90	51	(a)
2:3:2	do	2,000	2,000	1,470	880	520	310	150	100	60	30	(a)	
1:3:9	MT ₂ -CT-TiO ₂	2,200	1,300	900	700	800	1,150	1,400	1,500	1,700	1,650	1,600	1,400
4:1:4	MT-M ₂ T-CT	10,000	10,000	9,000	6,500	5,000	4,000	3,000	2,500	1,700	1,000	530	230
3:2:3	M ₂ T-MgO-CT	10,000	10,000	10,000	10,000	7,000	5,000	3,000	1,600	800	370	180	90
2:3:1	MgO-C ₃ T ₂ -CaO	2,000	2,000	1,300	870	500	370	190	160	70	40	(a)	
1:4:1	do	2,000	1,350	790	510	300	190	105	59	34	(a)		
M:C:S		The system MgO-CaO-SnO ₂											
2:6:7	M ₂ S-CS	1,500	550	150	55	60	65	75	95	110	130	190	190
4:1:1	MgO-CS	7,000	4,000	4,000	7,000	7,000	7,000	7,000	7,000	7,000	7,000	7,000	7,000
2:1:1	do	10,000	10,000	4,000	5,000	5,000	4,000	4,000	2,500	2,400	2,300	2,200	2,200
1:1:1	do	3,000	6,000	10,000	10,000	7,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
1:1:1 ^e	do	2,000	1,500	2,000	2,000	1,500	1,500	1,200	800	690	480	370	260
1:2:2	do	3,000	6,000	10,000	10,000	7,000	7,000	5,000	5,000	4,000	4,000	4,000	4,000
4:2:1 ^e	MgO-C ₂ S	440	260	240	230	240	240	230	220	180	150	110	80
2:2:1	do	1,400	1,400	1,000	950	820	780	780	750	720	720	720	640
1:2:1 ^e	do	1,500	1,000	800	500	330	200	130	95	65	45	35	25
C:S:T		The system CaO-SnO ₂ -TiO ₂											
1:3:1	CT-SnO ₂	2,000	2,000	620	680	880	870	700	570	370	240	150	80
1:9:1 ^e	do	20	30	30	(a)								
3:1:2	CT-CS	3,500	3,500	6,000	5,000	4,000	3,500	2,500	1,650	1,300	870	400	200
2:1:1	do			5,600		5,300	3,900	1,900	1,380	590	280	140	60
3:2:1	do			10,000	10,000	10,000	10,000	6,000	6,000	3,000	1,620	1,210	740
5:4:1	do	9,000	9,000	7,000	7,000	7,000	7,000	5,000	4,000	4,000	4,000	2,500	2,000
4:1:2 ^e	C ₃ T ₂ -CS	700	500	400	270	220	170	130	100	70	(a)		
6:3:2 ^e	do	1,450	860	620	380	290	200	150	110	85	55	(a)	
8:1:4 ^e	C ₃ T ₂ -C ₂ S	1,400	700	450	270	190	140	90	70	(a)			
7:2:2 ^e	do	140	90	70	70								
19:8:2 ^e	do	860	370	230	150	100	70	45	(a)				
1:3:9	CT-SnO ₂ -TiO ₂	10,000	9,000	2,000	1,900	750	640	580	390	350	200	110	70
2:2:3	do			2,400	1,900	1,400	1,400	1,300	1,300	1,300	810	650	350
2:1:4	do			2,600	2,500	1,900	1,800	2,200	1,700	980	440	220	100
3:2:2 ^e	CT-CS-SnO ₂	1,200	1,750	1,530	1,430	1,460	1,140	890	660	370	220	140	80
3:3:2	do	4,000	4,000	1,300	900	620	390	230	130	70	40	30	(a)
27:18:2 ^e	C ₃ T ₂ -CS-C ₂ S	850	450	360	210	180	120	90	70	50	35	25	20
6:3:1 ^e	do	1,000	610	460	250	220	160	110	75	50	40	25	20
M:C:S:T		The system MgO-CaO-SnO ₂ -TiO ₂											
8:1:4:1 ^b	M ₂ S-CT	6,000	2,000	1,200	1,100	1,000	900	700	600	560	500	400	280
4:1:2:1 ^b	do	4,000	1,600	900	800	800	1,000	1,000	1,000	1,000	1,000	800	500
2:1:1:1	do	5,000	5,000	5,000	5,000	5,000	5,000	4,500	2,000	1,500	870	390	200
2:2:1:2	do	3,500	3,500	3,500	2,000	4,500	4,000	3,000	1,400	1,000	620	380	190
2:5:1:5 ^b	do	4,000	4,000	4,000	3,000	3,000	3,000	2,000	1,500	990	360	220	120
2:9:1:9 ^b	do	2,500	2,500	2,500	1,400	1,300	1,300	1,200	910	590	380	200	110
2:1:1:2	M ₂ ST-CT	2,000	1,500	2,000	1,900	1,800	1,400	1,100	870	650	400	230	160
2:2:1:3	do	780	860	1,100	1,300	1,250	950	760	750	540	400	250	160
2:9:1:10 ^b	do	2,000	2,000	3,000	3,000	2,000	990	970	400	280	180	110	70
1:3:1:2 ^b	MgO-CT-CS	2,000	2,000	3,000	3,000	2,000	2,000	2,000	1,600	1,300	800	410	200
2:2:1:1 ^e	do	3,000	3,000	3,000	2,700	1,800	1,300	860	570	360	240	160	90
3:4:3:1	do	6,000	6,000	4,000	3,000	2,900	2,300	1,600	1,400	1,300	1,100	700	500
2:5:4:1	do	5,000	5,000	5,000	2,000	1,500	1,300	1,000	1,200	1,100	820	660	450
2:2:2:1	M ₂ S-CT-CS	1,800	570	1,390	2,750	2,700	2,670	2,630	1,740	1,410	1,280	1,270	1,080
3:1:1:2	M ₂ S-MT-CT	6,000	6,000	6,000	6,000	6,000	3,000	2,500	1,900	1,100	550	340	230
5:1:2:3	MT-M ₂ S-M ₂ ST-CT	1,400	1,400	1,400	1,900	1,900	1,300	950	630	340	210	130	
5:1:1:3	MT-M ₂ T-M ₂ S-CT	5,000	5,000	5,000	500	5,000	2,500	2,500	1,600	930	660	330	210
5:1:1:2	MgO-M ₂ S-M ₂ T-CT	1,600	2,400	930	910	810	760	720	680	560	400	270	170
4:3:2:2	MgO-M ₂ S-CS-CT	2,300	2,200	1,900	3,000	2,100	2,000	1,530	1,030	690	350	200	100
1:5:1:3	MgO-CS-CT-C ₃ T ₂	590	350	260	100	70	60	(a)					
1:6:2:2	MgO-C ₂ S-CS-C ₃ T ₂	760	560	440	250	210	170	150	120	95	65	40	25
1:6:1:2	MgO-CaO-C ₂ S-C ₃ T ₂	1,100	890	830	580	400	380	260	170	100	70	30	(a)
1:15:4:4	do	240	80	60	36	33	31	31	31	33	34	35	24

a See footnote a at end of table 14.

b See footnote b at end of table 14.

c See footnote c at end of table 14.

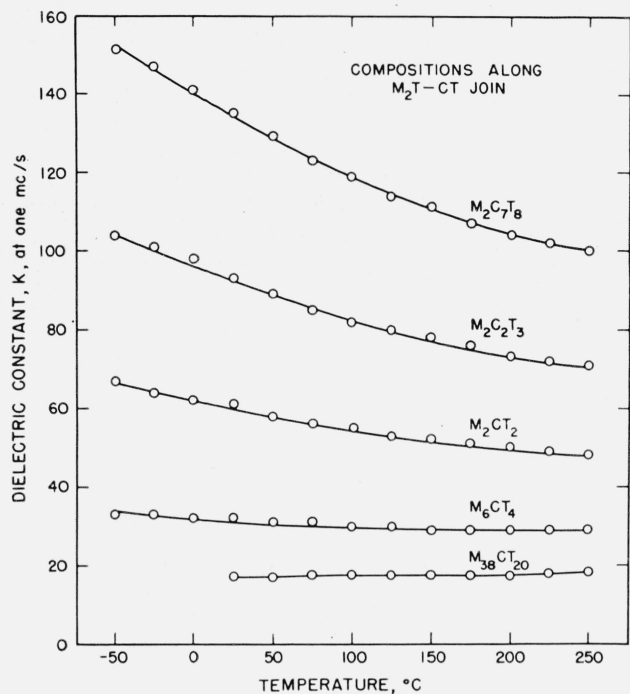


FIGURE 9. Effect of temperature variations on the dielectric constant of specimens along the M_2T -CT join.

especially along the MgO-CT join, when high-purity batch materials were used. Three specimens on the MgO-CT join were prepared with a commercial-grade perovskite, replacing the high-purity components usually used. Their maturing temperature was lowered more than 200°C by this change in components.

The dielectric properties of specimens on the binary joins were found to undergo a regular change with variations in the proportions of the end members. This change is illustrated in figure 9 for the dielectric constant, which varied from about 15 to about 165, depending on the compositions. The use of commercial-grade components caused a slight decrease in these values, together with the lowered maturing temperatures. The Q -values were good in all parts of the system, being, with a few exceptions, between 500 and 10,000.

Along the MT-CT, M_2T -CT, and MgO-CT joins, the temperature coefficient of dielectric constant (TCK) varied in a regular fashion as the composition was changed along the join (see fig. 9, in which this behavior is illustrated). It was found to be strongly negative near the CT end of the joins, and to approach zero or positive values as the percentage of CT in the specimen approached zero.

For specimens along the MgO- C_3T_2 join, the TCK values were irregular, showing shallow minima, and the values were numerically small.

4.2. The System MgO-CaO-SnO₂

The results of the dielectric tests on specimens from this system are listed in tables 13, 14, and 15. Specimens of these compositions are characterized by low K -values, high Q -values, and by a positive

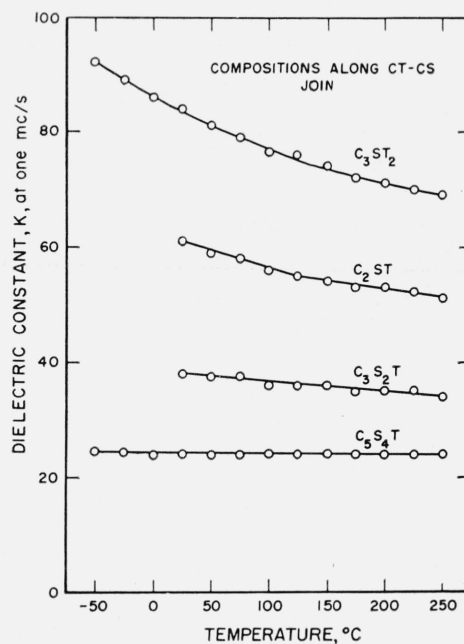


FIGURE 10. Effect of temperature variations on the dielectric constant of specimens along the CT-CS join.

temperature coefficient of K throughout the system.

Specimens along the MgO-CS join are noteworthy for the fact that they maintain a Q -value of several thousand, at temperatures as high as 250°C .

In some cases 1 percent of Fe_2O_3 was added as an aid in securing matured specimens. This additive was found to have the undesirable effect of lowering the Q -value, particularly at the higher temperatures.

4.3. The System CaO-SnO₂-TiO₂

The dielectric properties of specimens from this system are given in tables 13, 14, and 15. Maturing temperatures varied from $1,400^\circ$ to $1,550^\circ\text{C}$, depending on the composition. In a number of cases the use of a 1-percent addition of Fe_2O_3 as a flux or mineralizer was required in order to obtain matured specimens. The same effect probably could have been achieved by using less pure components.

Table 13 shows that the value of K changes regularly along the binary joins as the specimen composition changes from that of one end member to the other. The highest value of K noted was about 165 for the compound $\text{CaO}\cdot\text{TiO}_2$. The lowest values noted were 12 and 14 for the compounds C_2S and CS , respectively. No regular variation was noted in the Q -values. It may be observed, however, that these values were generally higher on joins having CT as an end member than they were on joins having C_3T_2 as an end member. This difference was probably due to the presence of Fe_2O_3 in the specimens on the latter joins.

Data concerning the variation of K and Q with temperature are listed in tables 14 and 15. On the binary joins, there was a regular variation of the temperature coefficient of K with composition. For example, see figure 10. A few specimens showed a

small negative TCK , and two specimens had a positive value. It is thought that not too much significance should be attached to the positive values and the smaller negative ones, as the specimens were semiconductors at the higher temperatures. This lower value may be caused by the Fe_2O_3 additive in these specimens.

4.4. The System $MgO-CaO-SnO_2-TiO_2$

The dielectric properties of the specimens in the quaternary system are about as would be expected from a knowledge of the ternary subsystems and from the knowledge that there are no quaternary compounds formed. The solid-solution development seems to result in an averaging of the properties of the compounds existing in the system. The results of the tests are listed in tables 13, 14, and 15.

The structure of the compound C_3T_2 seems to be very sensitive to small quantities of impurities. It was observed that the introduction of small amounts of MgO and C_2S into the C_3T_2 lattice caused very pronounced changes in the diffraction pattern of the material. The structural change seemed to be from a probable monoclinic symmetry to a very close approach to a cubic-perovskite symmetry, without, however, appreciable changes in the dielectric properties of the material.

5. Summary

A study of solid-state reactions in the system $MgO-CaO-SnO_2-TiO_2$ and its subsystems has been conducted. The results have either substantiated or shown that there exist in the system eight binary compounds, one ternary compound, and no quaternary compounds. Compatibility relations have been established for each of the four ternary subsystems and for the quaternary system. Extensive solid-solution formation was noted.

Dielectric-test samples were prepared and tested in each system except the system $MgO-SnO_2-TiO_2$, from which matured specimens were not obtained. Maturing temperatures were, in general, higher than $1,500^\circ C$. Values of the dielectric constant varied between 12 and 165, depending upon the composition of the specimen. For most samples tested, the temperature coefficient of K was negative, although the system $MgO-CaO-SnO_2$ is characterized by positive values. Values for Q of several thousand were found for most of the specimens studied. A number of test pieces maintained high Q -values at temperatures as high as $250^\circ C$.

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